DEVELOPMENT OF AN ANALYSIS FRAMEWORK FOR THE BEAM INSTRUMENTATION INTERFACE TO THE BEAM INTERLOCK SYSTEM AT ESS

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Abstract

The European Spallation Source (ESS) is currently being built in Lund, Sweden. When it is fully operational in 2025, it will host the most powerful neutron spallation facility in the world. The high-power proton beam needs to be carefully controlled and monitored in order to avoid possible damage to the sensitive equipment. Some of the most critical inputs to the beam interlock system are the beam monitors, delivered by the beam instrumentation group at ESS. In case local protection systems along the accelerator do not foresee a loss of beam, the beam monitors are the last line of defence to stop the proton beam and avoid equipment damage and consecutive downtime. It is essential for the protection of the machine that the whole beam permit signal chain, from monitors to actuators, fulfills strict reliability requirements. This paper describes the role and importance of the beam monitors to correctly measure beam losses and interface with the beam interlock system. It also describes one of several reliability studies that are performed to develop appropriate interfaces in the beam permit signal chain.

INTRODUCTION

When the European Spallation Source stands complete in 2025, it will house the most powerful neutron spallation source in the world. The 5 MW pulsed proton beam hits a rotating tungsten target, which knocks off a large number of neutrons per proton [1]. The neutrons are then moderated and guided to 22 scientific instruments, where research within a vast number of scientific fields is carried out.

The high-power proton beam and the tungsten target station need to be carefully controlled, monitored, and protected to deliver neutrons to the scientific instruments with very high reliability and availability. The machine protection system-of-systems (MP-SoS) [2] is set up to optimize beam availability and implement appropriate machine protection where necessary. The central system in the MP-SoS is the Beam Interlock System (BIS) [3], which takes critical input signals from sensors, monitors, and local protection systems (LPS), aggregates them into a central beam permit signal, and, when necessary, transfers this signal to the proton beam actuators to stop the beam. The most critical input signals to the BIS are those from the beam monitors, which monitor the current, position, and potential losses of the beam. In case the LPS in the different sections of the accelerator and target do not foresee a loss of beam, the monitors are the last line of

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defence to stop the proton beam and avoid equipment damage and consecutive downtime.

ESS RELIABILITY AND AVAILABILITY

ESS is facing high reliability and availability demands. As the success of the facility is based on the neutron research being conducted on site, there is a central strategy to address failures and downtimes at ESS [4]. In this strategy, machine protection has a central role in optimizing between stopping beam in order to avoid equipment damage and avoiding unnecessary beam stops that do not aid in protecting the machine.

Functional Protection at ESS

As a method to link the high reliability and availability goals with a robust machine protection strategy, the functional protection concept is under development at ESS. This concept highlights a set of protection functions that carry a qualitative as well as a quantitative part, similar to the field of functional safety [5]. The qualitative part defines what action the protection function takes in order to assure machine protection and optimize for highest reliability. As such, the inputs from sensors, monitors, and LPS trigger a protection function to take action, and their inherent accuracy and reliability are essential.

Based on the criticality of the protection function, the quantitative part defines what failure rate the protection function needs to fulfill in order to be successful. The higher the damage risk of a certain hazard, the higher the probability of completing the function needs to be, under the conditions and within the environment where the protection function is present. The method is extended from the IEC61508 standard [6], but targets (machine) protection rather than safety, and also includes the reliability and availability of the machine as a key feature.

THE BEAM MONITORS

To operate ESS successfully, it is essential that the accuracy of each beam stop is high. Each system that is required to run the accelerator, target, and neutron scattering systems, such as vacuum, cryogenics, focusing magnets, RF power, and interceptive devices, has an LPS that notifies the BIS in case something is wrong. However, for some scenarios, these LPS are not fast enough to detect and notify the BIS before damage occurs. In other scenarios, they might be broken or miss to send the signal for some other reason. To this end, the beam monitors are distributed along the accelerator and around the target to detect anomalies in and losses of the beam. The signal and control chain for the beam monitors are as seen in

Figure 1, and all steps need to fulfil the reliability specifications.

There are three types of beam monitors that are interfaced with the BIS, as described below. These monitors are developed, procured, and commissioned by the beam instrumentation group at ESS. It is important that their function and interface to the BIS fulfill the requirements of the protection functions where they are involved, as the monitors act as the last protection layer.

Beam Loss Monitors

The beam loss monitors (BLM) are totalling 276, and they are the primary beam monitors in the superconducting part of the accelerator [7]. The vast majority are of ionization chamber type, the same used in the LHC at CERN [8]. The BLMs are aggregated in groups of eight in their respective front-end electronics (FEE), then feed into digitizing and processing in the klystron gallery, where they later feed into the BIS.

Beam Current Monitors

There are 17 beam current monitors (BCM) along the accelerator [9]. As they measure the current through current transformers (ACCT), at least two monitors are needed to identify losses, where the difference in current between the monitors equals the losses. Machine protection at ESS will make use of this differential feature to compare currents between a number of locations in the accelerator, and just as with the BLMs, the interface to the BIS takes place after digitizing and processing in the klystron gallery.

Beam Position Monitors

The beam position monitors (BPM) are a total of 99 at ESS [10]. In the normal conducting part, they are of stripline type, while electrostatic button type is used in the superconducting part. As the BPMs measure position, rather than losses as such, they will be used to analyze trends in the beam behavior, rather than losses once an accident is taking place. For this purpose, some of the 99 BPMs will *not* be connected to the BIS. The interface to the BIS follows the same procedure as the monitors described above.

BEAM MONITOR ELECTRONICS AND BEAM INTERLOCK SYSTEM

As previously mentioned, the beam monitors are of utmost criticality for the protection of ESS, and their roles in several protection functions allocate high demands on their performance. There have been a set of proposed architecture options for this interface, and to identify whether the interface of monitors and their electronics to the BIS fulfills the quantitative needs of the protection functions, a working group has been created to define and establish a solution for the interface.

The different monitor types need different electronics setups, and due to this, the FEE varies with the monitors. The back-end electronics (BEE), in charge of the data processing through FPGA technology, however, is unified

throughout the beam monitoring system. This makes the monitor interface with the BIS generic, which allows for separate reliability studies of the monitors, the electronics, the BIS, and the actuator system. In a similar manner, the quantitative and qualitative requirements of the protection functions can be allocated to each system separately, as long as the full chain is used as the basis for the requirement allocation. A schematic view of the signal and control chain of the beam monitoring protection functions is seen in

ARCHITECTURE RELIABILITY STUDY

Method

A reliability study in the form of an FMEDA has been made for the proposed BIS architecture in [11]. As an extension for the beam monitoring protection functions, a study of four different architecture options for the BEE interface to the BIS was made and is described in detail in [12], using generic numbers for the components as listed in Table 1. As the design of the modules was not complete at the time of the study, the generic numbers fill the purpose within a comparative study rather than as an absolute study of system failure rates.

The four architecture options are named *Option A-D* in this paper, and they are graphically shown in Figure 2. *Option A* is a simple chain of the modules without any redundancy, included for comparative purposes. *Option B* has a separate electronics board where the BIS interface driver module is located, while *Option C* has an integrated interface driver module for the BIS inside the BEE. *Option D* has a tree structure where each BEE includes the BIS driver module and connects to a redundant pair of device interfaces (DIF) in the BIS.

The BEE and BIS interfaces were simulated in Relia-Soft BlockSim [13], using the four architecture options inside μTCA crates containing one (BLM), two (BCM), or three (BPM) digitizer boards, which are the likely configurations for the processing of beam monitor data for the three different monitor types [12]. The results for the crate configurations were then multiplied by the number of crates per monitor type. This gave an overview of what architectures that will be appropriate for further
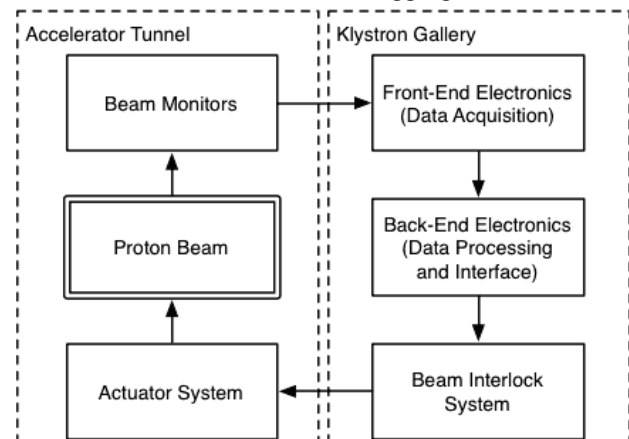

Figure 1: Signal and control chain of the beam monitoring protection functions.

development.

Table 1: Module mean time between failures (MTBF) for the three modules used in the study. The data is taken from [11] and [14].

Module	MTBF [h] False Trip	MTBF [h] Blind Failure
BIS_DIF	1.24E+05	2.68E+06
Digitizer Board	4.58E+05	9.93E+06
MP Board	1.83E+06	3.97E+07

The simulations were run for false trips (stopping beam when not necessary) and blind failures (missing to stop beam when there are losses), and MTBF as in Table 1 were applied to the modules. The false trips are important to keep as low as possible for the operational reliability of ESS and need to stay within the requirements of [4]. The blind failures, on the other hand, are critical for protection and need to be within the requirements specified for the protection functions.
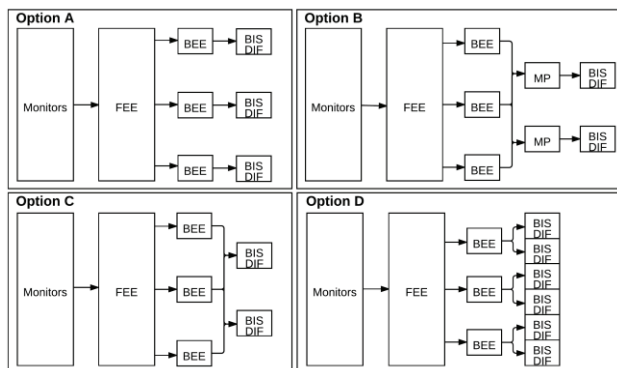

Figure 2: The four architecture options for the beam instrumentation BEE interface with the BIS. The Monitors and FEE are included for display purposes, but were not included in the analysis.

Results and Discussion

The outcome of the study is displayed numerically in Table 2 and graphically in Figure 3. As is seen, *Options B* and *C* have close to identical failure rates, with a slight advantage for *Option C* in terms of false trips.

Table 2: Failure rates for the four interface architecture options. Note that the units are arbitrary and are only fit for comparison purposes [12].

Architecture	False Trip Rate (a.u.)	Blind Failure Rate (a.u.)
Option A	3.44E-04	2.00E-05
Option B	3.82E-04	6.05E-06
Option C	3.67E-04	6.05E-06
Option D	5.80E-04	6.39E-06

As the exact specifications and designs, and thus the MTBFs, are not available for any of the modules at this point in time, this first conceptual study only displays what architectures are appropriate for further work, on a comparative basis. There are still ongoing discussions on the exact features of the digitizer boards, while the BIS needs to be benchmarked against a set of use cases before the design can be locked. The monitors have been selected, but the FEE still needs to be selected in detail. However, it is clear that the work should continue with *Options B* and *C*, and the final distinction can only be made once the data is available for the constituents in the analysis.
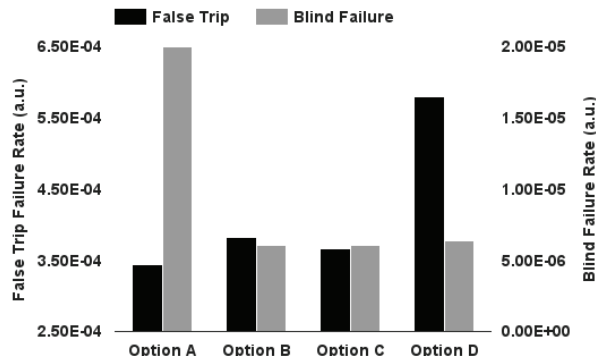

Figure 3: Comparative diagram of the four interface architecture options.

FUTURE WORK

There is still plenty of necessary work to be able to do an in-depth reliability analysis where the failure rates can be taken as absolute rather than comparative. This work will continue during the coming year, and includes the selection and finalizing of the FEE and BEE designs, benchmarking of and decision on the exact BIS architecture, and a detailed reliability study of the actuator system.

While this paper suggests the road forward in the quantitative aspect of the protection functions, the qualitative behavior of the protection functions will be outlined in detail in the coming year. This is necessary for correct implementation and application of machine protection in order to fulfil the reliability and availability goals of ESS.

CONCLUSIONS

The machine protection work at ESS proceeds with the development of a functional protection concept that targets both protection and reliability. A set of protection functions is identified, which calls for both qualitative and quantitative requirement specifications. The beam monitors are the last line of defence for the protection of the ESS equipment, and thus have high demands to perform as intended. The study presented in this paper is one out of many in the development and decision-making within machine protection and the interface between the BIS and its input systems.

ACKNOWLEDGEMENTS

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